The Selection of a Radiation-Tolerant DAC for the LHC (Part I: Bipolar Technology)

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***Abstract.* - The control system electronic of the LHC cold mass will require the use of 12-bit parallel input data converters and they must tolerate the radiation that will be generated by the particle beam. In this paper, we show the radiation tests on some DAC's built in bipolar technology. During the irradiation, the offset & gain error and the relative number of bits were on-line measured. A brief description of the measuring system will be shown. After the deactivation of radioactive isotopes, the consumption and the frequency behaviour were checked. All these data were used to select the DAC which will be employed in the control of the LHC cold mass.**

In the next paper, the results when testing CMOS converters will be shown.

***Index Terms.* - COTS, digital-to-analog converters, radiation tolerance, fast bipolar device, LHC.**

I. INTRODUCTION

As a part of the collaboration agreement between the Cryogenic Division of the Large Hadron Collider (LHC) of CERN and the Universidad Complutense de Madrid, the selection of the electronic devices to be used on the development of the temperature control system of the cold mass has been carried out.

The requirements for the DAC to be used in the instrumentation are: 12 parallel inputs and toleratant to the radiation that will be generated along the collider ring. Previous simulations have shown that there will be a leakage of neutral particles and gamma rays in the order of 10^{13}-10^{14} n·cm^{-2} and several hundreds of Gy for 10 years.The total radiation tests were carried out at the Portuguese Research Reactor (Sacavem, Portugal). The devices received about $3 \cdot 10^{13}$ n·cm^{-2} and a vestigial total gamma dose about 1200 Gy. The neutron energy spectrum is almost constant between 0.6-3 MeV and negligible outside these values. The irradiation took place in five sessions of about 12 h followed by other stand-by 12 h.

There were two research lines: Fast bipolar & CMOS technology devices. The first technology is very sensitive to the neutron radiation, which damages the semiconductor lattice and removes the minority carriers. The gamma radiation affects in the same way but its damage capacity is less important. The effects on the second technology will be described in the next part.

II. DEVICE MEASUREMENT SYSTEM

The system used to measure the characteristics of the devices during the irradiation consisted of a personal computer, where a program developed in Testpoint was running, and some instrumentation devices: A Keithley 7002 switch system, a K2002 digital multimetre and K236 source measure unit. The PC used the standard GPIB protocol to control all the devices. Moreover, the PC has got a digital PIO12 card that was managed by the program to provide the digital 12-bit input to the converters. The PC could charecterized the converters every few minutes during the irradiation, which usually takes nine or ten days. The devices were placed on test boards and they were connected to the digital multimetre and the power supplies by a low resistance & shielded 4-metre wire. All the devices were supplied by an uninterrupted power source (UPS) to minimize the action of accidental power cuts. A detailed description of this system can be found at [1].

The program made a digital input sweep to get information about the main non-idealities of the DAC's: Offset & gain errors and the relative number of bits. Complete information about these parameters can be found at [2]. The tested devices were AD565AJD & AD667JN, from Analog Devices, and DAC703KH, from Burr-Brown. The datasheets of these devices can be found in the manufacturers' web page. Usually, the offset & gain errors are measured in least significative bits (LSB). This unit is defined as:

$$1\ LSB = \frac{Range}{2^N} \qquad (1)$$

where *Range* is usually the reference voltage and *N* is the number of bits. E. g., on the AD565AJD & AD667JN converters, the range is equal to the reference voltage (10 V) so 1 LSB is 2.44 mV. On the other converter, the reference voltage is around 6.3 V but the range is 20 V and 1 LSB is 4.88 mV. Moreover, bipolar DAC's usually have an internal voltage reference that must be measured during the irradiation.

The AD565AJD converter needs an operational amplifier to convert current to voltage due to it has a current output. However, the amplifier can suffer its own degradation so it must be placed outside the reactor. After the irradiation, the shift of the consumption and the frequency behaviour was checked.

On the other hand, the temperature inside the reactor was monitorized during the irradiation. The temperature kept always around 30-35 ºC.

III. RESULTS

A) AD565AJD

Several samples of this device received between $2.51\cdot10^{13}$ $n\cdot cm^{-2}$ & 1200 kGy and $3.28\cdot10^{13}$ $n\cdot cm^{-2}$ and 1300 Gy. The most sensitive parameter is the value of the internal voltage reference (fig. 1). There is a great increase of this parameter (~32 mV/10^{13} $n\cdot cm^{-2}$). This is related to the growth of the line regulation coefficient, very usual in the voltage references when they are irradiated. When the neutron fluence is about $2.6\text{-}2.7\cdot10^{13}$ $n\cdot cm^{-2}$, the voltage falls suddenly down to 8 V. It goes on decreasing softly until the end of the irradiation. The final value is about 6.9 V. Some days later, the voltage became around 10 V because of the partial recovery of the lattice.

The offset & gain errors keep almost constant during the irradiation. Only a sample suffered a sudden increase of the gain error up to 1000 LSB when the neutron fluence was about $3\cdot10^{13}$ $n\cdot cm^{-2}$. This error increase was not found in the other samples. The initial relative number of bits was about 11 and does not shift during the irradiation.

A consumption decrease was found. E.g., a sample, which received $3.28\cdot10^{13}$ $n\cdot cm^{-2}$ required before the irradiation 12.73 mA and, after it, only 11.11 mA. On the other hand, before the irradiation, the converter output needed 120 ns to change from –10 V to 0 V and, after the tests, this value has not changed. Therefore, we conclude that there is no change of the frequency response in this level of radiation.

B) AD667JN

These devices showed an increase of the voltage reference. However, the rise is only 10-12 mV when the highest neutron fluence is reached (Fig. 2). The offset

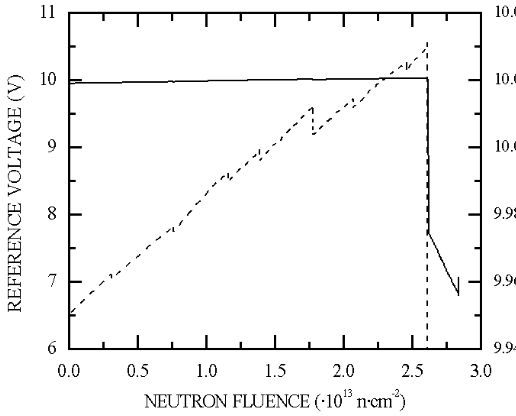

Fig.1: Evolution of the AD565AJD voltage reference. The continuous line shows the evolution of the parameter all over the full range of values and is related to the left Y-axis. The dash line is a zoom of the parameter when its value is around 10 V and the scale is shown by the right Y-axis.

error is the most modified parameter. When the neutron fluence is $0.8\text{-}0.9\cdot10^{13}$ $n\cdot cm^{-2}$, the offset error grows very quickly up to 22 LSB (Fig. 3). The growth goes on but the slope is more and more low until reaching a maximum of 40-45 LSB at $1.3\cdot10^{13}$ $n\cdot cm^{-2}$. Next, the higher the neutron fluence, the lower the offset error.

Even, during the following stand-by times, the lattice annealing makes the offset error increase. The gain error remains quite constant although a small decrease was found (~1 LSB/10^{13} $n\cdot cm^{-2}$). The relative number of bits decrease according to the neutron fluence although its value is always higher than 12.5 bits. Finally, a decrease of consumption and a worsening of frequency response were observed. The first parameter shifted from 19.76 mA to 17.50 mA on the most irradiated devices. The shift of the frequency parameters is much stronger: A converter took about 0.5 µs to change the output from 0 to 10 V before the irradiation. After it, it takes more than 7 µs.

C) DAC703KH

Two samples of this device received $3.25\cdot10^{13}$ $n\cdot cm^{-2}$ & 1270 Gy. This is a 16-bit converter so the four least significative bits were grounded. The voltage reference output is about 6.3 V and, unlike the other converters, it is not directly related to the value of the full-scale range (+10 V → -9.9951 V). Curiously, the value of the voltage decreased with the neutron fluence in contrast to other voltage references (Fig. 4), discrete or integrated in other devices as DAC's. On the other hand, the offset error softly increases but, when the error is about 20 LSB, the offset error starts growing very rapidly (fig. 5). The required neutron fluence to reach this value depends a lot on the sample: One of them needed $1.8\cdot10^{13}$ $n\cdot cm^{-2}$ and the other one $2.6\cdot10^{13}$ $n\cdot cm^{-2}$. Whatever the fluence level was, the slope is always higher than 100

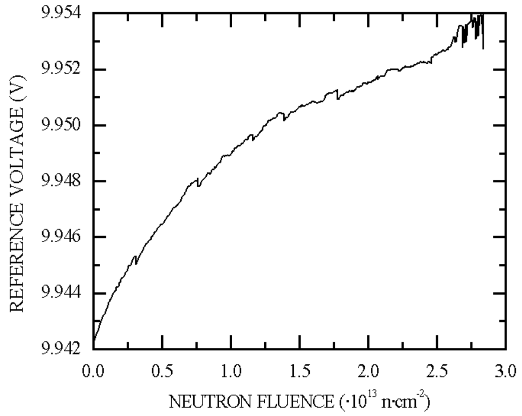

Fig.2: Evolution of the internal voltage reference of the AD667JN.

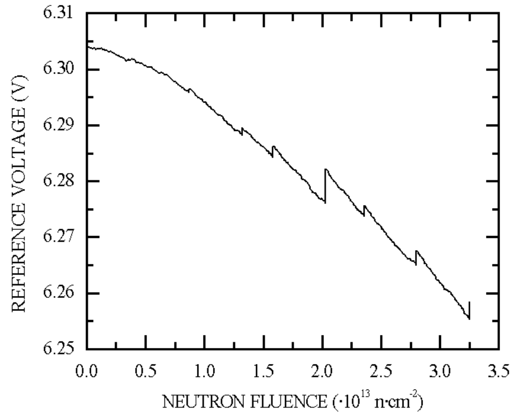

Fig. 4: The voltage reference of the DAC703KH converter. The sharp increases are a result of the stand-by times, where the annealing of the lattice vanishes partially the damage.

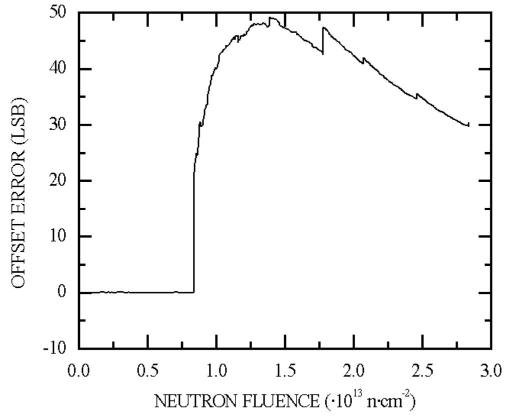

Fig. 3: The AD667JN offset error. The great increase of 22 LSB at $8 \cdot 10^{12}$ n·cm^{-2} took place during the irradiation. The other little jumps of the graph are results of the annealing during the stand-by times and they are not similar to the first sudden growth.

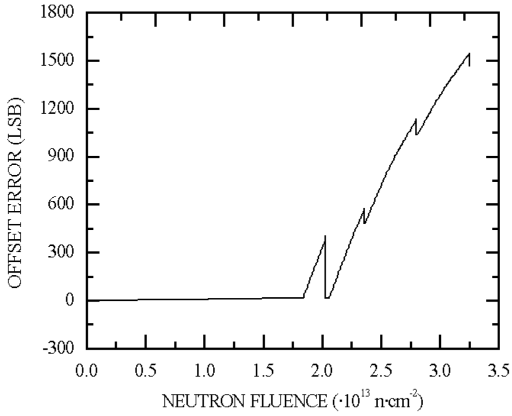

Fig. 5: Offset error of DAC703KH. The quick diminution of the value is a consequence of the reactor stop and the partial annealing of the devices.

LSB per 10^{12} n·cm^{-2}. The evolution of the gain error is similar to the offset error and, finally, the relative number of bits is shown in fig. 6.

The cause of the diminution of the relative number of bits is originated by the change of the input-output function. Fig. 7 shows the relationships between the input and the output at different fluence values. In the beginning, the function is a straight line from 10 V to –10 V. After, the output becomes a broken line since the inputs lower than the offset error cannot be correctly converted. Thus, the function is very non-linear and this causes that the relative number of bits decreases a lot. A similar reason explains the increase of the gain error because of its dependence on the offset error.

IV. DISCUSSION

The change of the characteristics cannot be exactly explained unless knowing the internal structure of the device and this is a manufacturer's secret. However, most changes can be understood. The neutron radiation provokes the increase of the semiconductor resistivity, decrease of the bipolar transistor gain, etc. [3]. Therefore, the external DC characteristics and the accuracy must be changed bythe variation of the internal devices.

The strange jump on AD667JN could not be explained. The information given by the manufacturer was not enough to settle a believable theory about its origin. In the case of DAC703KH, the strange shape of the input-output function could be related to the degradation of the internal operational amplifier. One of the most degraded opamp parameters is the short circuit current, as a consequence of the damage on the output stage. In [6], some irradiated operational amplifiers had short circuit currents in the order of 1 mA or lower. On the other hand, the negative short circuit current is usually less affected than the positive one. The DAC703KH belongs to a family of 16-bit accuracy converters and its main characteristic is that it has got an internal operational amplifier to convert the output from current to voltage. The DAC702KH converter is a similar device

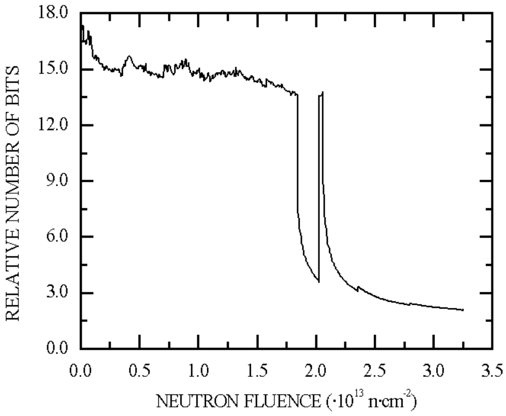

Fig. 6: The relative number of bits on irradiated DAC703KH. The fast rise observed around $2{\cdot}10^{13}$ $n{\cdot}cm^{-2}$ corresponds to a reactor stand-by time.

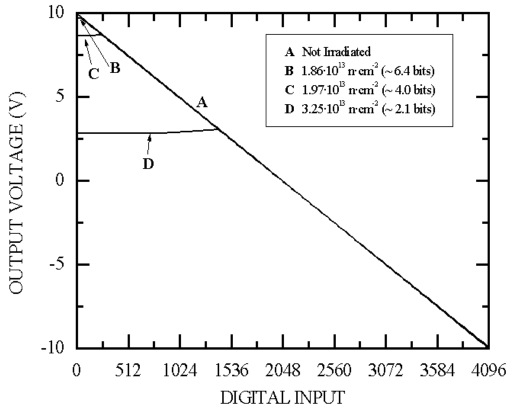

Fig. 7: Relationship between the digital input and the output of the DAC703KH converter. All the functions are similar if the input is high but the differences are very big in the range of low inputs.

that has not got any internal operational amplifier and and it forces the auxiliary operational amplifier to supply about 1 mA when the digital input is 0. All these data lead us to believe that the origin of the accuracy loss is the degradation of the internal operational amplifier.

The consumption decrease is usual in bipolar devices when irradiated with neutrons, such as the authors have checked in other devices [4-5] and it is confirmed by other results found in different public databases [6]. On the other hand, the worsening of the frequency response of simple bipolar devices is well known so a similar result in complexer devices should not be strange.

V. CONCLUSION

Although there was a parallel research line (see the following paper), the results were not as good as the shown in this paper. Weighting all the data, we conclude that the AD667JN & DAC703KH converters are more interesting than the AD565AJD if the neutron fluence is lower than 10^{13} $n{\cdot}cm^{-2}$. However, due to those ones are very sensitive to the neutron fluence between 10^{13} & $3{\cdot}10^{13}$ $n{\cdot}cm^{-2}$, their use is refused for the benefit of AD565AJD. Although this one is a little less accurate, it tolerates total radiation doses in the same order as the predicted one around the LHC ring. Its main handicap is the reference voltage and the external operational amplifier. However, discrete radiation tolerant devices have just been found (OPA627AP, REF102CP or special CERN rad-hard regulators) [5, 7].

Further, total radiation tests of the whole converter system (AD565AJD + OPA627AP + External reference) will be carried out to be completely sure of its radiation tolerance.

VI. REFERENCES

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